Beyond Standard Cosmology: New Statistical Approaches to Lorentz Invariance Violation

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Based on Universe 11 (2025) 68 (arXiv:2501.06022) and Physics of the Dark Universe (arXiv: 2504.18416)

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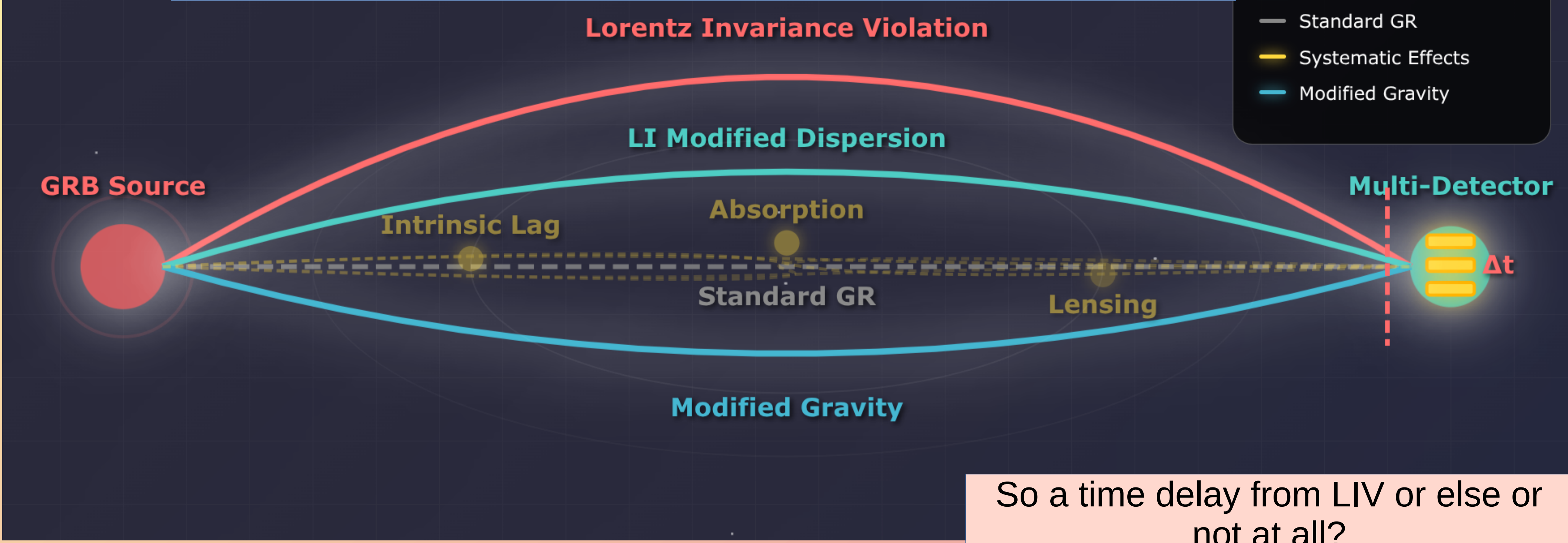
ИЯИЯЕ INRNE

БЪЛГАРСКА АКАДЕМИЯ на НАУКИТЕ 1869

The possible origins of apparent time delays

Lorentz invariance – the equivalence of physical laws in all inertial reference frames

QG Time Delay – the delay in arrival time due to MDR



So a time delay from LIV or else or not at all?

QGTime delays

- Some quantum gravity theories predict **modified dispersion relation**

$$E^2 = p^2c^2 \quad \longrightarrow \quad E^2 = p^2c^2\left[1 - s_\pm\left(\frac{E}{\xi_n E_{QG}}\right)^n\right],$$

- This leads to **changed group velocity**

$$v(E) = \frac{\partial E}{\partial p} \simeq c\left[1 - s_\pm \frac{n+1}{2}\left(\frac{E}{E_{\mathrm{QG,n}}}\right)^n\right].$$

- The modified velocity leads to a **modified time of flight of the photons:**

$$t = \int_0^z \left[1 + \frac{E}{E_{QG}}(1+z')\right]\frac{dz'}{H(z')}$$

$$\Delta t_{LIV} = \pm s\frac{\Delta E}{E_{QG}}\int_0^z (1+z')\frac{dz'}{H(z')}$$

Addazi et al , Prog.Part.Nucl.Phys. 125 (2022)
arXiv: 2111.05659

$$\frac{\Delta t_{obs}}{1+z} = a_{LIV}K + \beta\,,$$

$$K \equiv \frac{1}{1+z}\int_0^z \frac{(1+\tilde{z})\,d\tilde{z}}{h(\tilde{z})}\,.$$

$$a_{LIV} \equiv \Delta E/(H_0 E_{QG})$$

The GRBs Pros/Cons/Complications

- Pros:

  -- high energies (E_{iso}>10^{52}erg)

  -- high redshifts (z~9)

  -- very high energy emissions (~TeV)

  -- numerous observations

- Cons:

  - no ultimate GRB model,**intinsic lag?**

  - propagational effects

  - signal extraction

- **Cosmology?**

$$\Delta t_{\rm obs} = \Delta t_{\rm int} + \Delta t_{\rm QG} + \Delta t_{\rm spec} + \Delta t_{\rm DM} + \Delta t_{\rm gra}$$

Intrinsic lag

- Standard assumption – constant term Ellis et al. 2005, Shao 0911.2276

$$\frac{\Delta t_{obs}}{1+z} = a_{LIV} K + \beta \,,$$

- For a single GRB in multiple channels or multiple GRBs – energy fit: Du et al. 2010.16029, Wei 1612.09425, Desai et al. 2205.12780, Xiao et al. 2022, Agrawal 2102.11248

$$\Delta t_{\rm int,z}(E) = \tau \left[\left(\frac{\mathcal{E}_0}{1\ \rm keV} \right)^{-\alpha} - \left(\frac{E}{1\ \rm keV} \right)^{-\alpha} \right],$$

- Luminosity dependence Vardanyan et al. 2212.02436

$$\tau^{{\rm int},i}_{\rm RF} = \frac{\tau^{{\rm int},i}_{\rm obs}}{1+z} = \beta_{\rm long} \left(\frac{L^i_{\rm iso}}{L_*} \right)^{\gamma},$$

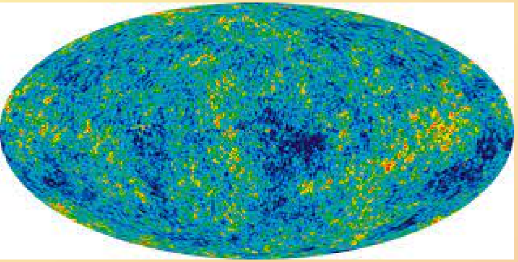
Let’s include cosmology properly…

CMB

GRB

BAO

SN



NASA/WMAP

z~1100

Cruz deWilde / Swift / NASA

z~6

BOSS

z~2

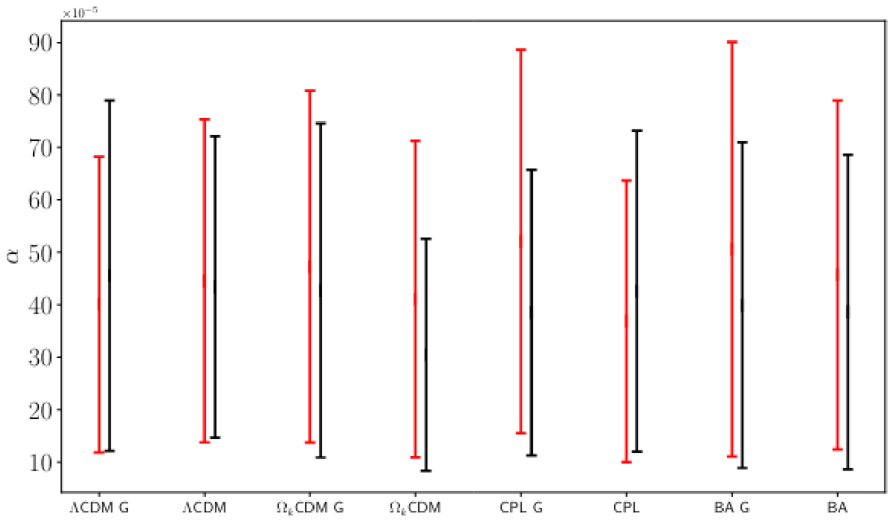
NASA/ESA/CSA WEBB

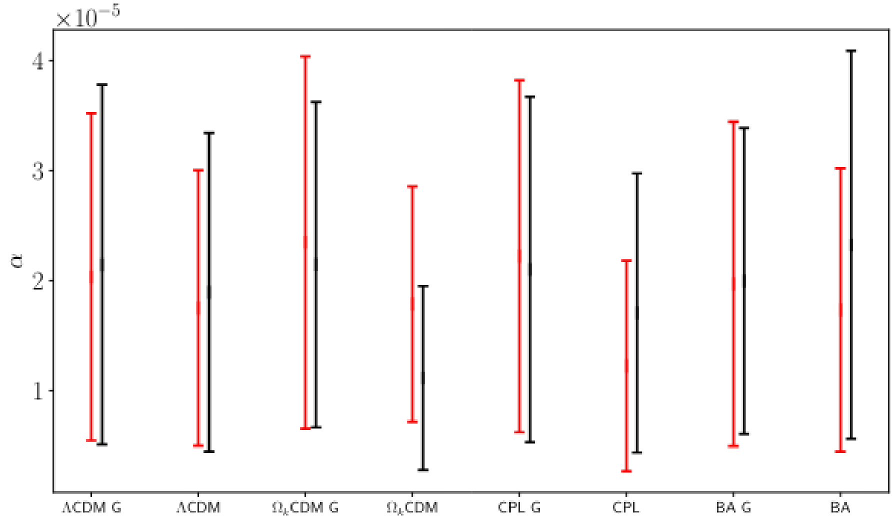
z~2

For all, we solve the Friedmann equations:

$$H(z)/H_0 = E(z)$$

$$E(z)^2 = \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_{DE}(z),$$





TD1: Ellis et al. 2006
35 GRBs,
wavelet method

β and ɣ weakly constrained

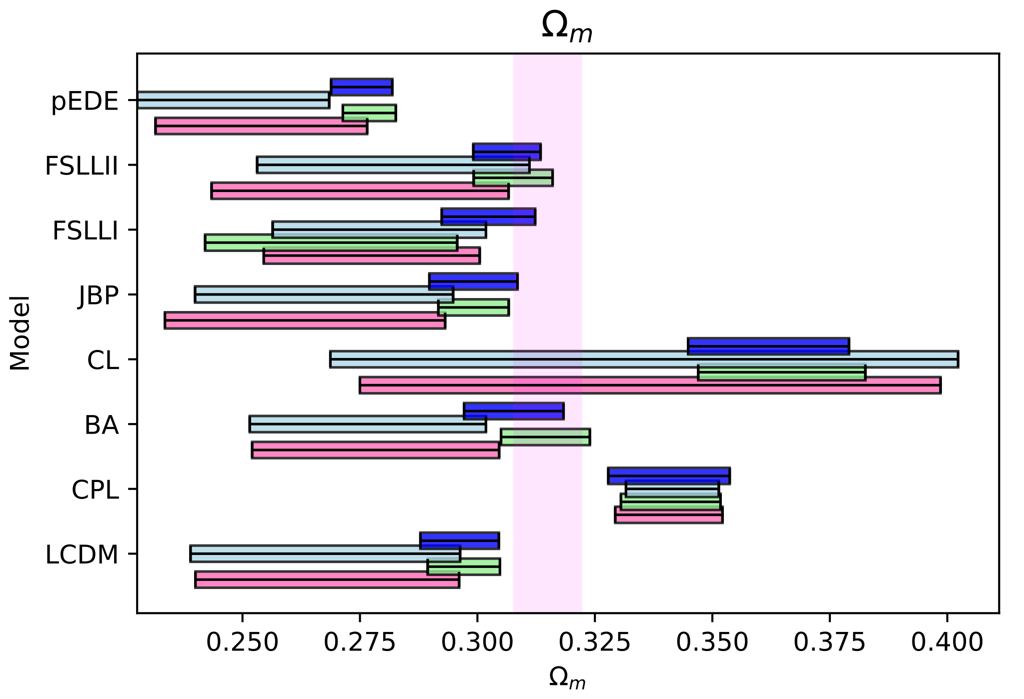
Vardanyan et al. 2022,
49 GRBs,
descrete CCF

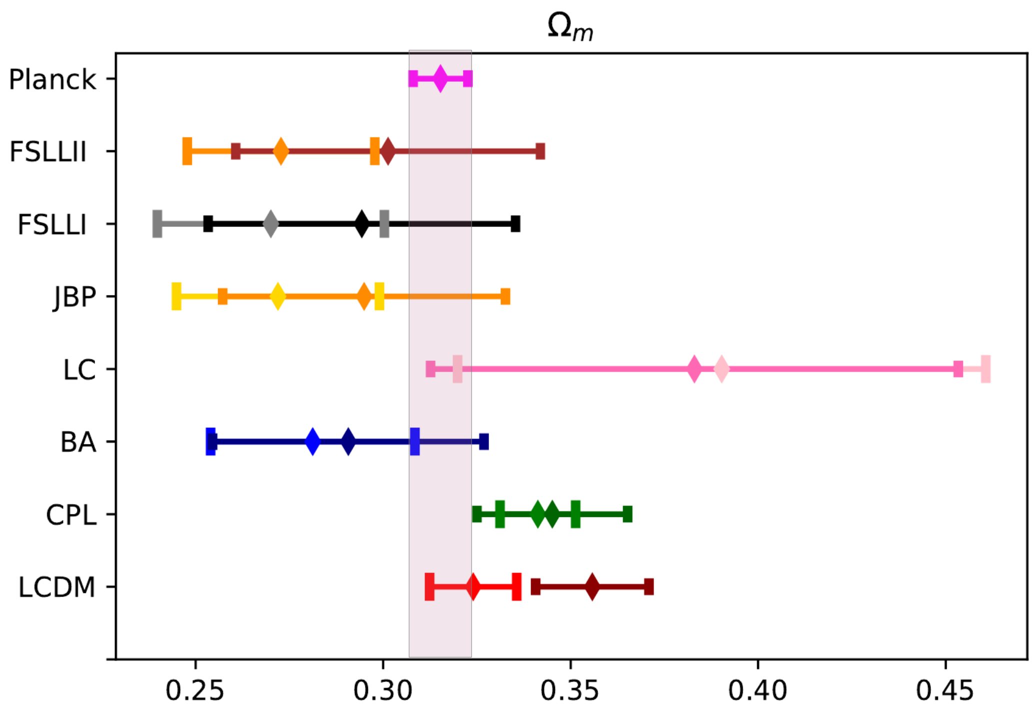
Dataset	$E_{QG}^{min,SA} \times 10^{17}$Gev	$E_{QG}^{max,SA} \times 10^{17}$Gev	$E_{QG}^{min,EA} \times 10^{17}$Gev	$E_{QG}^{max,EA} \times 10^{17}$Gev
$H_0 = 73.04 \pm 1.04$				
TD1	1.14 ± 0.84	0.81 ± 0.57	1.39 ± 1.01	0.93 ± 0.68
TD2	48.0 ± 35.6	35.5 ± 25.5	74.6 ± 55.9	35.8 ± 27.1
$H_0 = 67.4 \pm 0.5$				
TD1	1.24 ± 0.91	0.88 ± 0.62	1.51 ± 1.09	1.01 ± 0.735
TD2	48.0 ± 35.6	35.5 ± 25.5	74.6 ± 55.9	35.8 ± 27.1

The results: Ω_m

BAO+CMB (darker) and BAO+CMB+SN+GRB(lighter)

D.S., Universe 2022, 8(12), 631



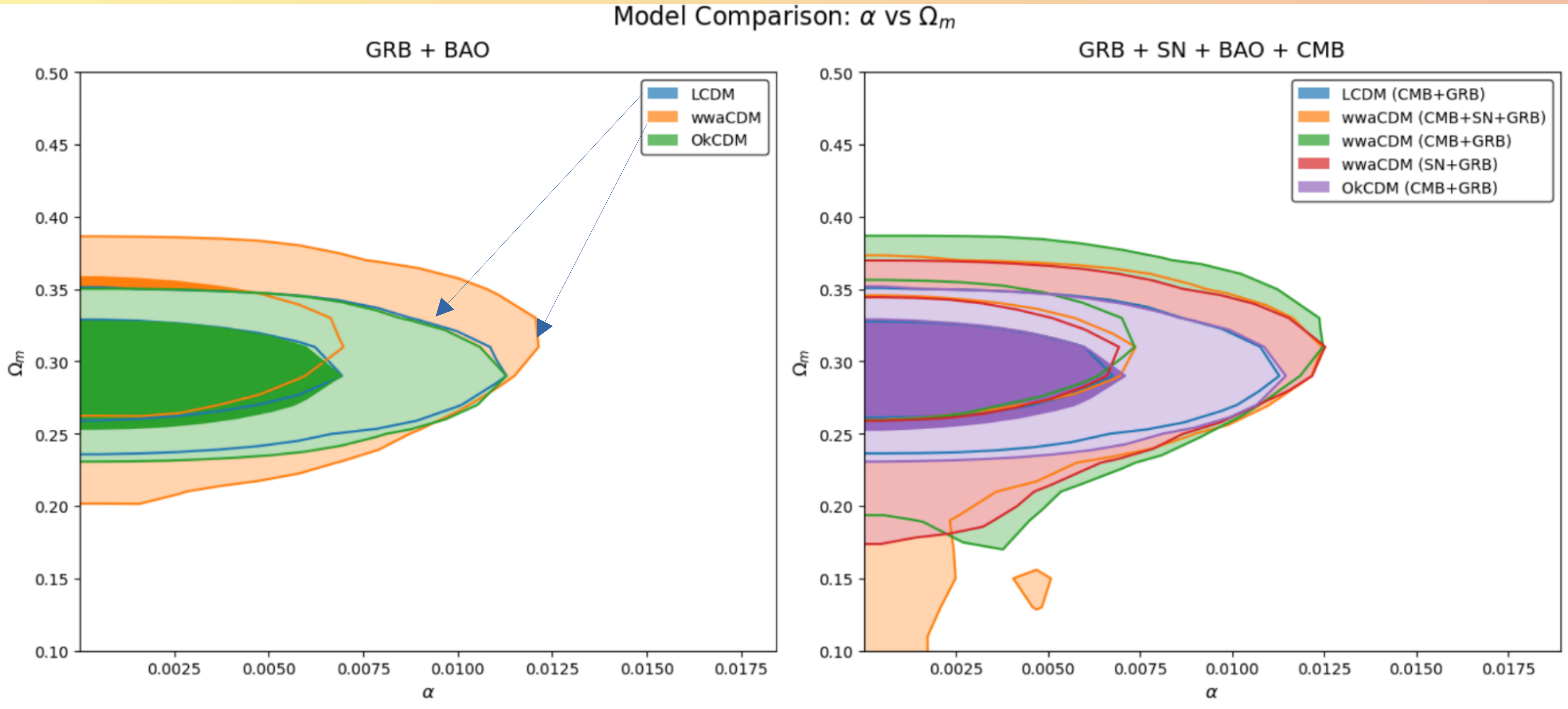


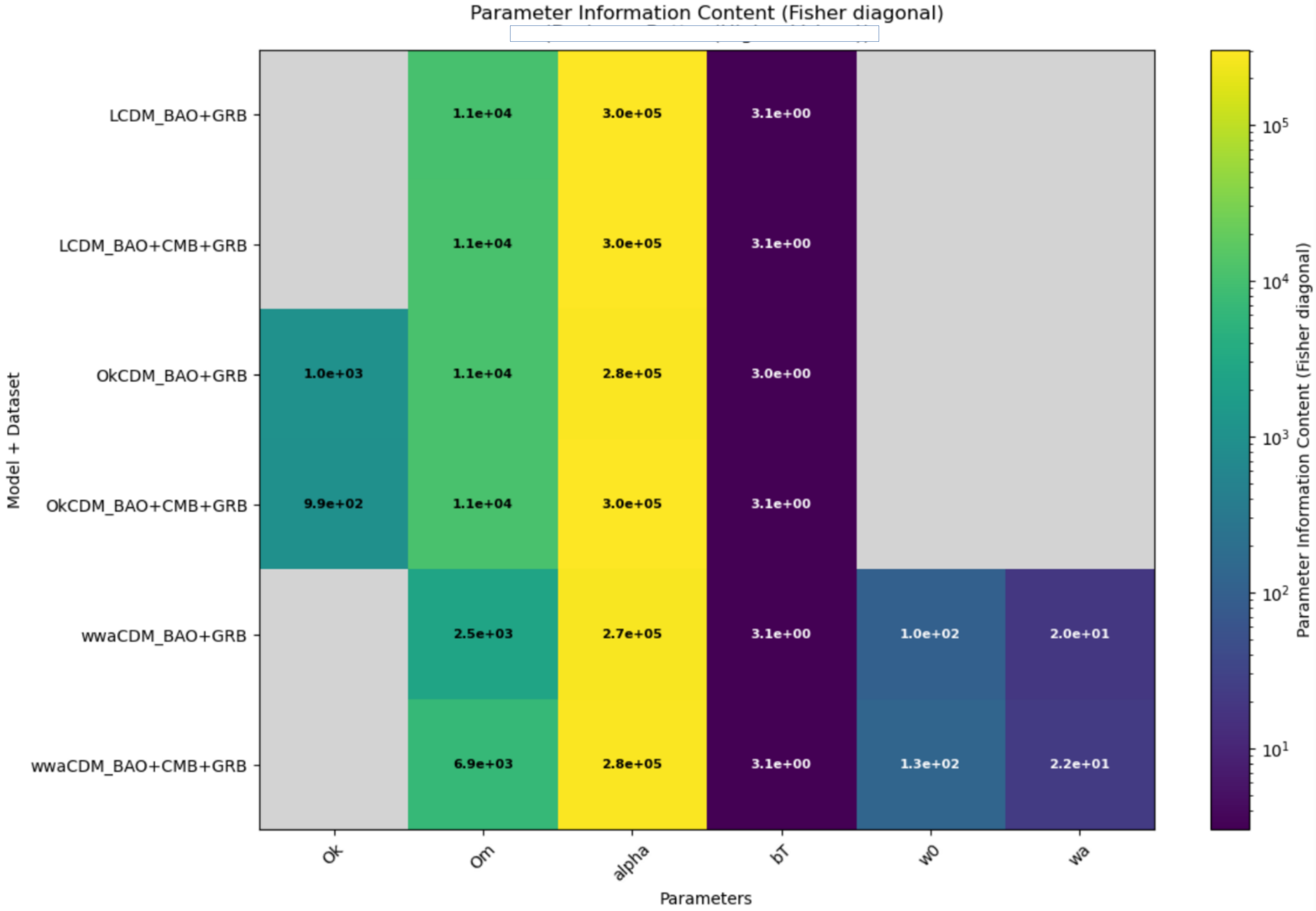
With TD

Class. Quantum Grav. 40 195012, 2023

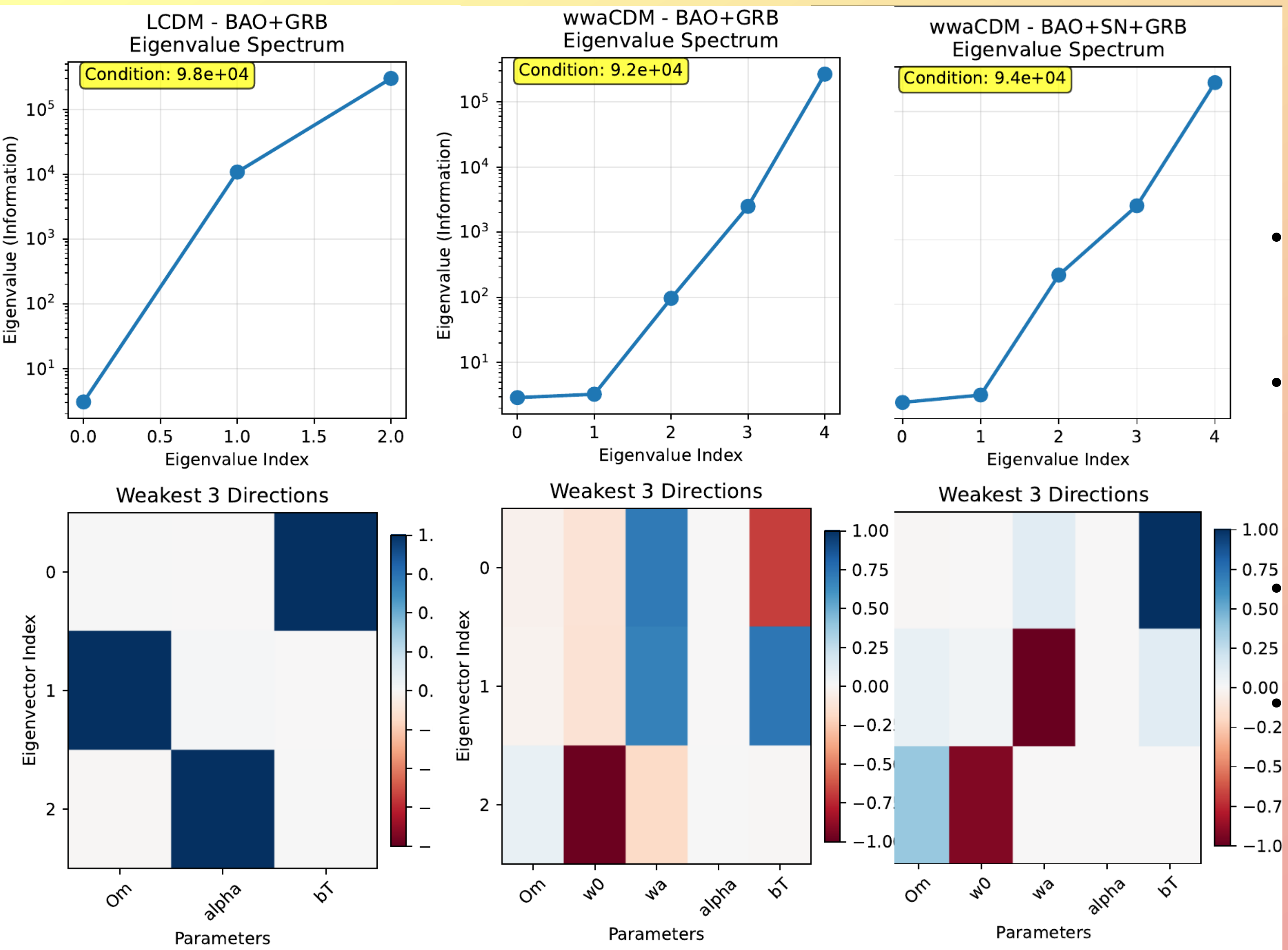
Without

Comparing the models





Parameter Information Content (Fisher diagonal)
LCDM_BAO+GRB
LCDM_BAO+CMB+GRB
OkCDM_BAO+GRB
OkCDM_BAO+CMB+GRB
wwaCDM_BAO+GRB
wwaCDM_BAO+CMB+GRB
Model + Dataset
Ok
Om
alpha
bT
w0
wa
Parameters
1.1e+04
3.0e+05
3.1e+00
1.1e+04
3.0e+05
3.1e+00
1.0e+03
1.1e+04
2.8e+05
3.0e+00
9.9e+02
1.1e+04
3.0e+05
3.1e+00
2.5e+03
2.7e+05
3.1e+00
1.0e+02
2.0e+01
6.9e+03
2.8e+05
3.1e+00
1.3e+02
2.2e+01
10^5
10^4
10^3
10^2
10^1
Parameter Information Content (Fisher diagonal)

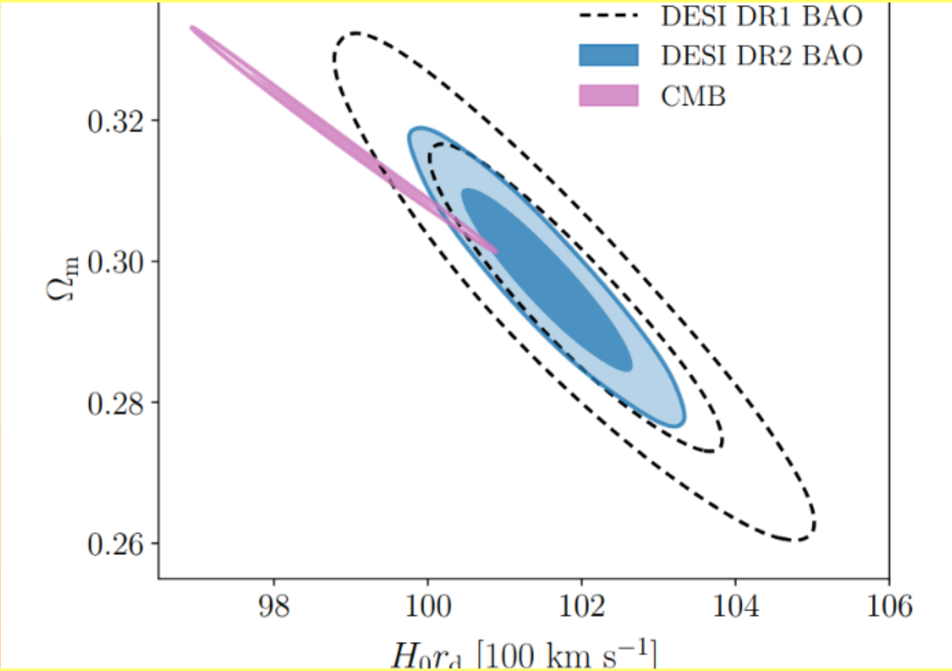


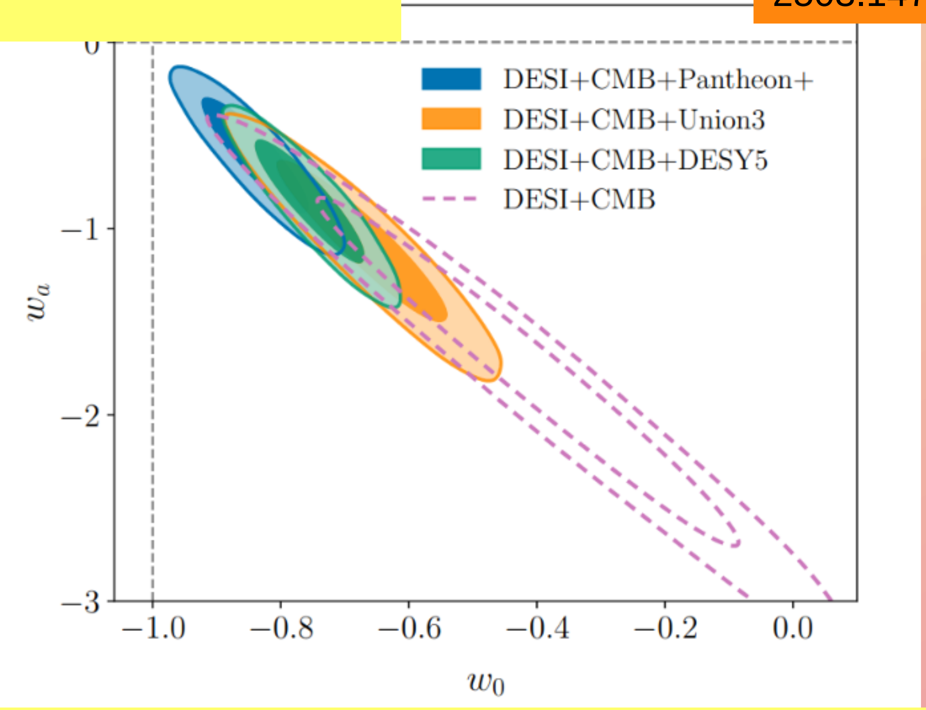
- Using the Fisher matrx, we can study the information content of the posteriors
- We see big difference between the eigenvectors and possible correlation between the parameters.
- Adding more parameter with wwaCDM only worsen the situation.
- Adding SN decreases the degeneracy focusin it beween DDE parameters

The state of the Hubble tension

The Hubble tensions is at 5.3σ as of 2023! 4.5σ from DESI+BBN
The novelty: 1.7σ-3.3σ evidences for wwaCDM!

DESI collab., 2503.14738

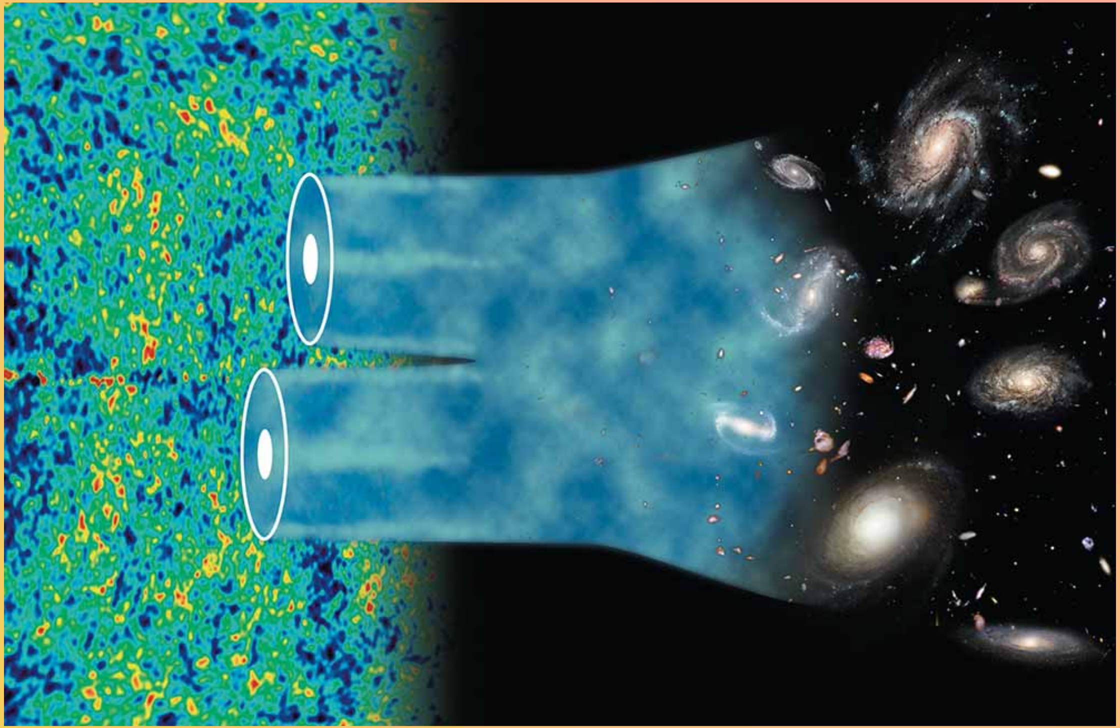




The uncertainty in cosmology makes LIV detection even harder.

While α shows good statistical precision, the systematic robustness remains questionable due to the degeneracies.

Thank you for your attention!



The quantities we use

- SN/GRB

$$\mu_B(z) - M_B = 5\log_{10}[d_L(z)] + 25\,,$$

- CMB distance priors

$$l_A = (1+z_*)\frac{\pi D_A(z_*)}{r_s(z_*)},$$

$$R \equiv (1+z_*)\frac{D_A(z_*)\sqrt{\Omega_m}H_0}{c},$$

- BAO

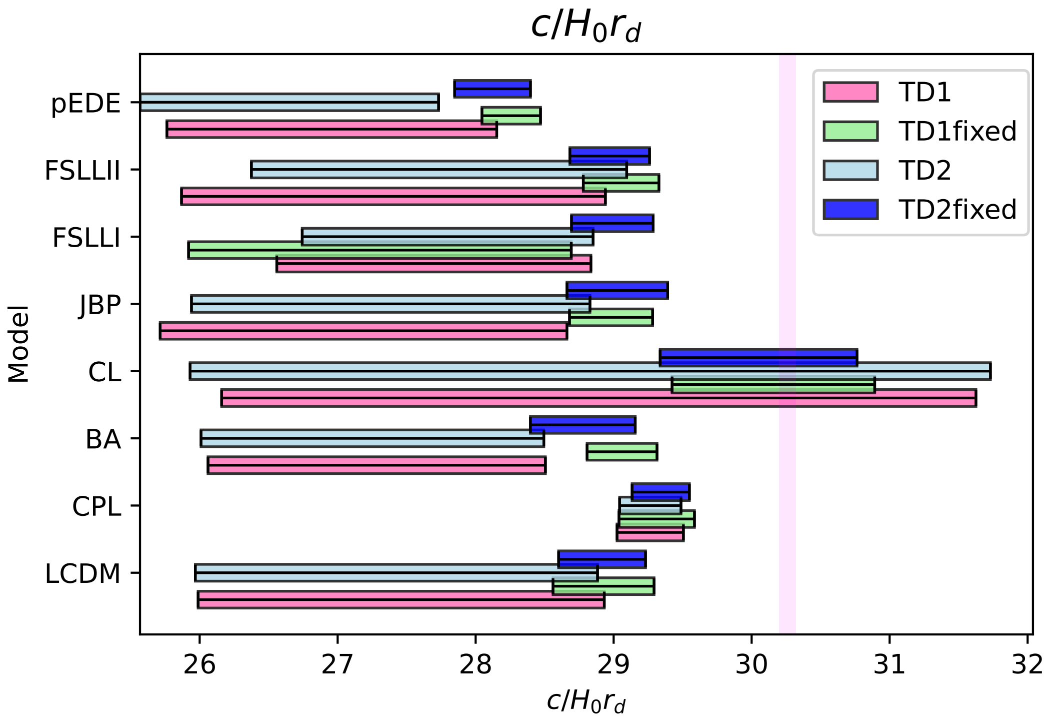
$$D_A = \frac{c}{(1+z)H_0\sqrt{|\Omega_k|}}\mathrm{sinn}\left[|\Omega_k|^{1/2}\int_0^z \frac{dz'}{E(z')}\right]$$

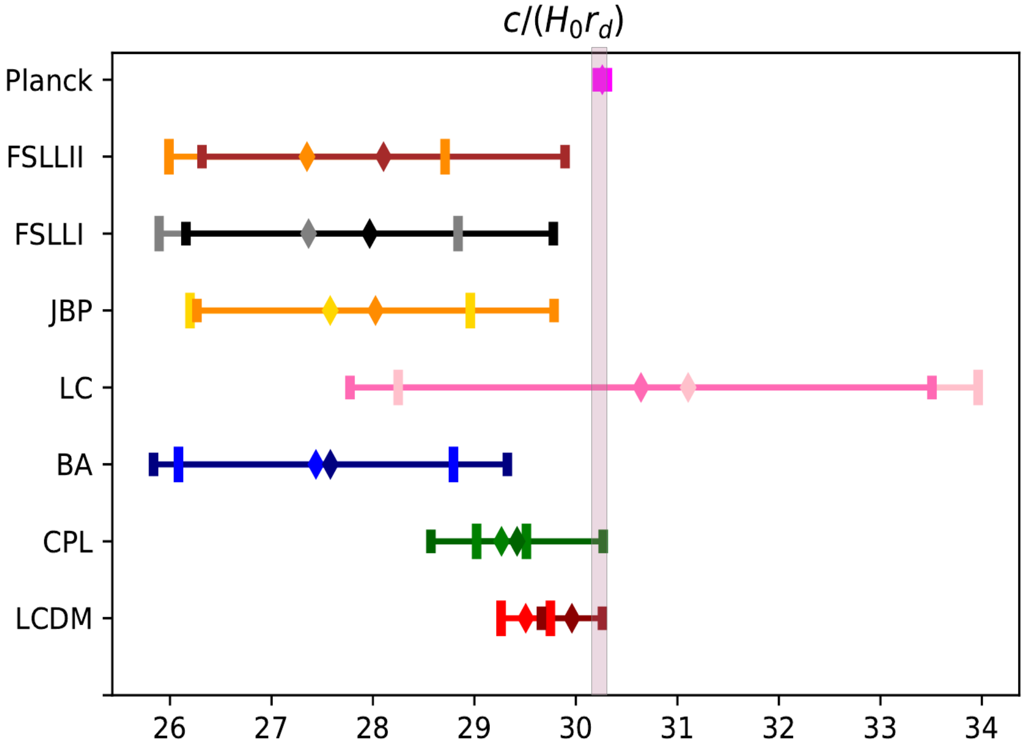
where

$$S_k(x) = \begin{cases} \frac{1}{\sqrt{\Omega_k}}\sinh\left(\sqrt{\Omega_k}x\right) & \text{if} \quad \Omega_k > 0 \\ x & \text{if} \quad \Omega_k = 0 \\ \frac{1}{\sqrt{-\Omega_k}}\sin\left(\sqrt{-\Omega_k}x\right) & \text{if} \quad \Omega_k < 0. \end{cases}$$

All depend on c/H_0r_d so we take it as 1 factor!

c/H_0r_d





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